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## Tropospheric reactive odd nitrogen over the South Pacific in austral springtime

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**Abstract.** The distribution of reactive nitrogen species over the South Pacific during austral springtime appears to be dominated by biomass burning emissions and possibly lightning and stratospheric inputs. The absence of robust correlations of reactive nitrogen species with source-specific tracers (e.g.,  $C_2H_2$  [combustion],  $CH_3Cl$  [biomass burning],  $C_2Cl_4$  [industrial],  $^{210}Pb$  [continental], and  $^7Be$  [stratospheric]) suggests significant aging and processing of the sampled air parcels due to losses by surface deposition, OH attack, and dilution processes. Classification of the air parcels based on CO enhancements indicates that the greatest influence was found in plumes at 3–8 km altitude in the distributions of  $HNO_3$  and peroxyacetyl nitrate (PAN). Here mixing ratios of these species reached 600 parts per trillion by volume (pptv), values surprisingly large for a location several thousand kilometers removed from the nearest continental areas. The mixing ratio of total reactive nitrogen (the  $NO_x$  sum), operationally defined in this paper as measured ( $NO + HNO_3 + PAN + CH_3ONO_2 + C_2H_5ONO_2$ ) + modeled ( $NO_2$ ), had a median value of 285 pptv within these plumes compared with 120 pptv in nonplume air parcels. Particle  $NO_3^-$  was not included in this analysis of the  $NO_x$  sum due to its 10- to 15-min sampling time resolution, but, in general, it was <10% of the  $NO_x$  sum. Comparison of the two air parcel classifications for  $NO_x$  and alkyl nitrate distributions showed no perceivable plume influence, but recycling of reactive nitrogen may have masked this direct effect. In the marine boundary layer, the  $NO_x$  sum averaged 50 pptv in both air parcel classifications, being somewhat isolated from the polluted conditions above it by the trade wind inversion. In this region, however, alkyl nitrates appear to have an important marine source where they comprise 20–80% of the  $NO_x$  sum in equatorial and high-latitude regions over the South Pacific.

### 1. Introduction

Reactive odd nitrogen species play central roles in tropospheric photochemistry. The concentration of  $NO_x$  ( $NO + NO_2$ ) controls photochemical production or destruction of  $O_3$ , and it also influences the concentration of  $HO_x$  ( $OH + HO_2$ ). Ozone and  $HO_x$  are important since they largely determine the oxidizing capacity of the troposphere. Because of the high chemical reactivity of  $NO_x$ , it is often converted photochemically to  $HNO_3$  and the reservoir species peroxyacetyl nitrate (PAN). These conversions take place in a matter of hours during the summertime [Logan, 1983; Kasting and Singh, 1986]. Reactive nitrogen can be transported over long distances as  $HNO_3$  and PAN, and they may eventually react to regenerate  $NO_x$  in remote areas. Removal of reactive nitrogen from

the troposphere is primarily by wet and dry deposition of  $HNO_3$  and particle  $NO_3^-$  [Logan, 1983].

Total reactive odd nitrogen ( $NO_y$ ) has been defined as the sum of the individual species which are reactive in the troposphere. These species include  $NO$ ,  $NO_2$ ,  $NO_3$ ,  $N_2O_5$ ,  $HNO_3$ ,  $HONO$ , PAN,  $RONO_2$  ( $R = \text{alkyl}$ ), and particle  $NO_3^-$ . Together this suite of compounds has also been estimated by measurement of  $NO_y$  as  $NO$  using a gold catalytic converter and a reductant such as  $CO$  [Bradshaw *et al.*, 1998]. In air parcels without recent emission inputs these two measures of  $NO_y$  often disagree [Fahey *et al.*, 1986; Atlas *et al.*, 1992a; Sandholm *et al.*, 1994; Bradshaw *et al.*, 1998]. Some of these differences may be due to certain species, such as organic nitrates, not being measured on an individual basis, but they are still included in the more general  $NO_y$  measurement [e.g., Atlas *et al.*, 1992a]. In addition, some  $NO_y$  converters appear to convert non- $NO_y$  compounds (e.g.,  $NH_3$  and  $HCN$ ) with varying efficiency [Kliner *et al.*, 1997; Bradshaw *et al.*, 1998]. However, surprisingly good agreement in measured  $NO_y$  and the  $NO_x$  sum was found recently for the upper troposphere over the North Atlantic [Talbot *et al.*, 1999a]. The reasons for varying degrees of agreement are unclear, and it may be more meaningful to measure the individual species and use their sum as representative of  $NO_y$  (the  $NO_y$  sum). This approach has been adopted by the NASA Global Tropospheric Experiment (GTE) program and is the one used in this paper.

The distribution of reactive odd nitrogen species and the mechanisms that control their concentrations are not well understood for large areas of the global troposphere. This is particularly

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true for the South Pacific, and as such these measurements were an integral component of the NASA Pacific Exploratory Mission-Tropics (PEM-Tropics) A airborne expedition over this region during September-October 1996. This paper presents the distributions and interrelations of measured NO, HNO<sub>3</sub>, PAN, CH<sub>3</sub>ONO<sub>2</sub>, and C<sub>2</sub>H<sub>5</sub>ONO<sub>2</sub> plus modeled NO<sub>2</sub> over the South Pacific during PEM-Tropics A.

## 2. Experimental Methods

### 2.1. Study Area

The PEM-Tropics A airborne expedition was conducted using the NASA Ames DC-8 research aircraft. Transit and intensive site science missions comprised 18 flights, averaging 8-10 hours in duration and covering the altitude range of 0.3-12.5 km. The base of operations progressed as follows: (1) Tahiti (three missions), (2) Easter Island (two missions), (3) Tahiti (one mission), (4) New Zealand (one mission), and (5) Fiji (three missions). The overall scientific rationale and description of individual aircraft missions are described in the PEM-Tropics A overview paper [Hoell *et al.*, 1999]. The features of the large-scale meteorological regime and associated air mass trajectory analyses for the September-October 1996 period are presented by Fuelberg *et al.* [1999]. The data used in this paper were obtained in the geographic grid approximately bounded by 60°N - 75°S latitude and 165°E - 105°W longitude. A geographic map with the flight location details is shown in several prior papers [e.g., Hoell *et al.*, 1999]. The measured and model-calculated parameters utilized in the present paper are available from the NASA Langley Distributed Data Archive Center (DDAC) or the GTE project archive (ftp-gte.larc.nasa.gov).

### 2.2. Sampling and Analytical Methodology

**2.2.1. NO.** Nitric oxide was measured with the Georgia Tech two-photon/laser-induced fluorescence instrument [Bradshaw *et al.*, 1985; Sandholm *et al.*, 1990]. This technique is spectroscopically selective for NO. The system incorporated recent advancements in laser detection hardware as well as improvements in the airborne sampling manifold [Bradshaw *et al.*, 1999]. The inlet consisted of a 100-mm ID glass-coated stainless steel flow system which skimmed and dumped to exhaust the air flow nearest the walls. The inlet was mounted in a 45° orientation to the fuselage and utilized a ram air flow rate of 40,000 L min<sup>-1</sup>. This high flow rate created a "pseudo-wall-less" sampling environment in that nearly all NO<sub>x</sub> species that may have interacted with the walls would not have time to make it back to the volume element being sampled in the central core of the manifold before being exhausted overboard. Thus NO was measured in the center core flow only, minimizing potential wall artifacts [Bradshaw *et al.*, 1999]. Wall effects were also greatly reduced by steering the two probe beams (sampling an area of <1 cm<sup>2</sup>) through the center of the sampling manifold which itself had a cross-sectional area of ~80 cm<sup>2</sup>. Given a 10-Hz probe frequency, this high flow rate also permitted adequate time for a complete turnover of the sampling region between laser shots, thus ensuring that measurements of NO were being made under true ambient conditions. The measurements were reported using an integration time of 1 s. Accuracy of the instrument calibration is estimated to be ±16% for NO at the 95% confidence limit.

**2.2.2. NO<sub>2</sub>.** Model-calculated NO<sub>2</sub> was used here instead of the Georgia Tech measured NO<sub>2</sub> due to better time overlap with the other NO<sub>x</sub> sum measurements. It should be noted that the measured and modeled NO<sub>2</sub> data were highly correlated, giving a (NO<sub>2</sub>)<sub>meas</sub>/(NO<sub>2</sub>)<sub>calc</sub> ratio of 0.93 [Bradshaw *et al.*, 1999]. The

Harvard photochemical point model was used to calculate NO<sub>2</sub> along the DC-8 flight path from diurnal steady state concentrations of radicals and chemical intermediates estimated using the ensemble of observations from the aircraft [Schultz *et al.*, 1999].

**2.2.3. HNO<sub>3</sub>.** Acidic gases were subsampled from a high-volume (500-1500 standard liters per minute sLpm) flow of ambient air using the mist chamber technique [Talbot *et al.*, 1997a; Talbot *et al.*, 1999b]. The subsample flow rate was always <10% of the primary manifold total flow. Sample collection intervals were typically 4 min in the boundary layer, 6 min at 2-9 km altitude, and 8 min above 9 km altitude, reflecting decreased pumping rates in the middle and upper troposphere. The inlet manifold consisted of a 0.9-m length of 41-mm ID glass-coated stainless steel pipe. The pipe extended from the DC-8 fuselage to provide a 90° orientation to the ambient air streamline flow. To facilitate pumping of the high-volume manifold flow on both the HNO<sub>3</sub> and Georgia Tech systems, a diffuser was mounted over the end of the inlet pipe parallel to the DC-8 fuselage. This device provided a "shroud" effect, slowing the flow of ambient air through it to slightly below the true air speed of the DC-8 and adding 50-100 hPa of pressurization to the sampling manifold. This effectively eliminated the reverse venturi effect (~40 hPa) on the sampling manifold. An additional feature of the diffuser was a curved step around the manifold pipe, which provided the streamline effects of a backward facing inlet. Its function was to facilitate exclusion of aerosol particles greater than ~2 μm in diameter from the sampling manifold. Aerosols smaller than this were removed from the sampled airstream using a 1-μm pore-sized Zeflur Teflon filter that was readily changeable every 5-10 min to minimize aerosol loading on the filter and gas/aerosol phase partitioning from ambient conditions. The accuracy of the HNO<sub>3</sub> measurements is estimated to be ±20%, with a precision ranging from ±10 to 35% depending on the ambient mixing ratio.

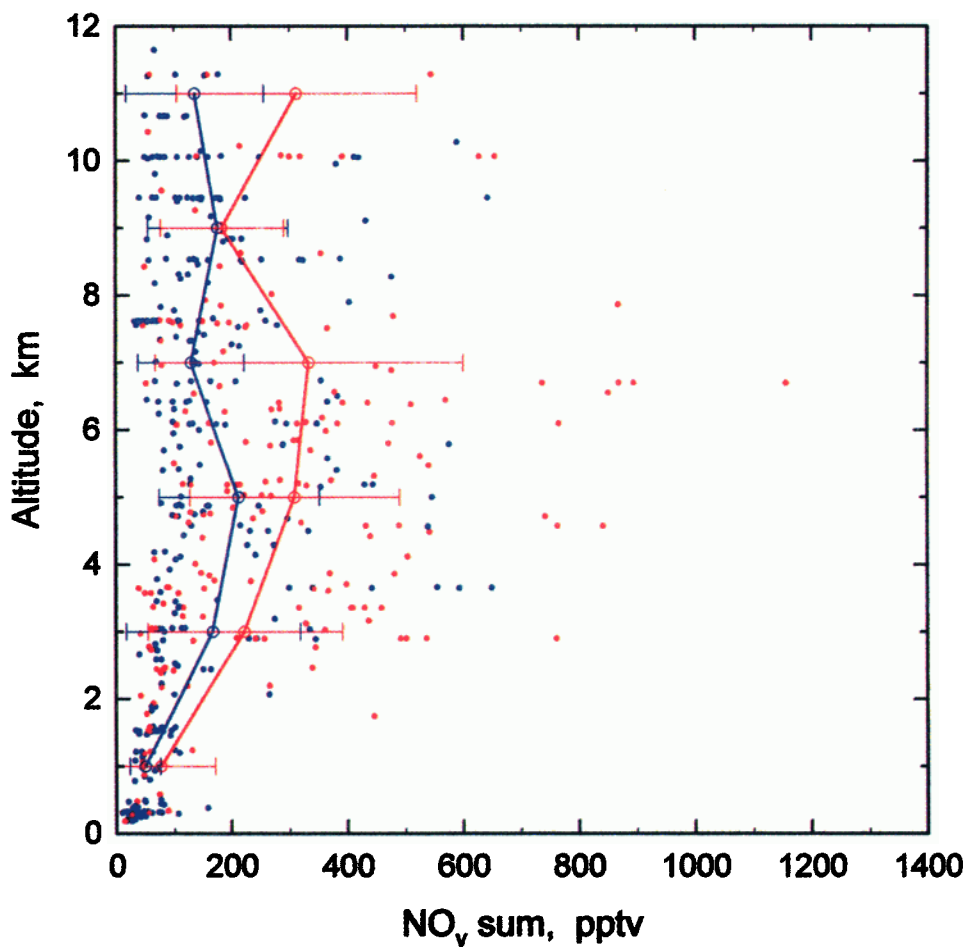
**2.2.4. PAN.** The NASA Ames PAN instrument provided measurements of this species using electron capture gas chromatography detection from a cryogenically enriched sample of ambient air [Singh and Salas, 1983; Gregory *et al.*, 1990]. The system uses an aft facing Teflon inlet with the instrument operated at a constant pressure of 1050 mbar isolated from aircraft cabin pressure fluctuations. The sampling time of 2 min was followed by a 5-min analysis time. In-flight calibration was accomplished using PAN synthesized in liquid *n*-tridecane. The PAN measurements have an estimated accuracy of about ±20% and a precision of ±10%. The detection limit for PAN was 2-3 parts per trillion by volume (pptv).

**2.2.5. Alkyl Nitrates.** C<sub>1</sub>-C<sub>4</sub> alkyl nitrates were collected in stainless steel canisters and then separated analytically on a Restek-1701 column and quantified by electron capture detection [Atlas *et al.*, 1992b]. Oxygen doping enhanced the sensitivity of the electron capture detection for the alkyl nitrates. The precision is ±5% at mixing ratios above 5 pptv and ±10% below this value.

## 3. Results

### 3.1. Database

The data in this paper used the timescale defined by the HNO<sub>3</sub> measurements, with all other species (including calculated NO<sub>2</sub>) averaged to this time base. The data set was further refined by using only time periods where there was a measurement reported for all the reactive nitrogen species. This reduced the size of the merged product by about 50%, but it still allowed meaningful comparisons for the NO<sub>x</sub> sum with other parameters, as data from each mission and a wide altitude span were included. Again, for the purposes of



**Plate 1.** Vertical distribution of the  $\text{NO}_y$  sum in nonplume and plume air parcel classifications. Blue dots are nonplume data, and red dots are from within combustion plumes. The open circles represent the average value  $\pm$  one standard deviation for 2 km altitude bins.

this paper,  $\text{NO}_y$  is defined as the sum (the  $\text{NO}_y$  sum) of the individual species  $\text{NO}$ ,  $\text{HNO}_3$ , PAN,  $\text{CH}_3\text{ONO}_2$ ,  $\text{C}_2\text{H}_5\text{ONO}_2$  plus model-calculated  $\text{NO}_2$ . The higher alkyl nitrate species were  $<1$  pptv and present inconsistently, so they are not included in this analysis of the  $\text{NO}_y$  sum.

Because of the significant impact of aged biomass burning emissions over the South Pacific in austral springtime [Gregory *et al.*, 1999; Schultz *et al.*, 1999; Talbot *et al.*, 1999b], the data were divided into two groups: (1) within biomass combustion plumes and (2) nonplume air parcels. The combustion data set corresponds to sampling times where CO was enhanced  $>10$  ppbv in plumes well defined by CO,  $\text{O}_3$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  (J. A. Logan *et al.*, manuscript in preparation, 1999).

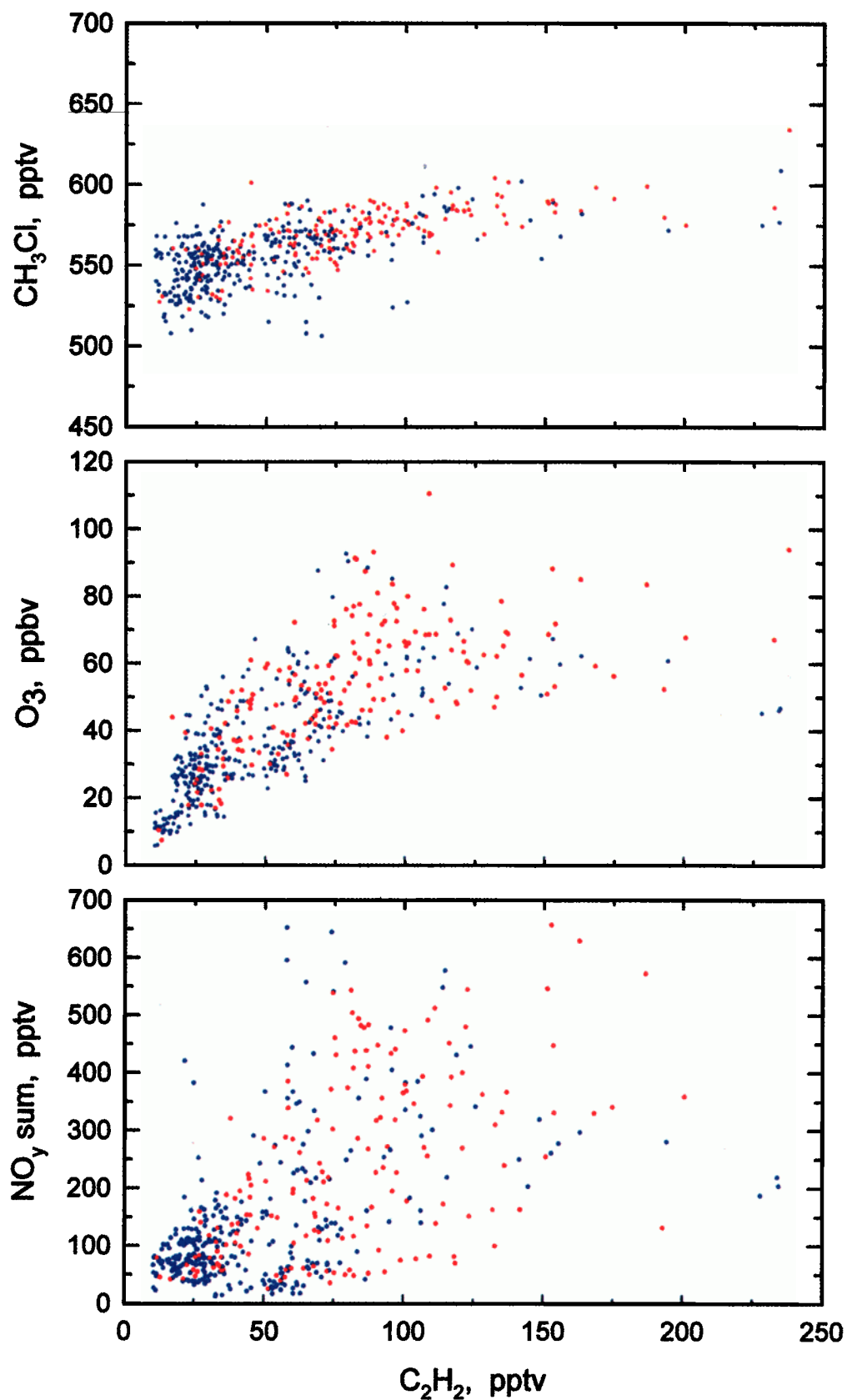
Although not discussed in detail this paper, particle  $\text{NO}_3^-$  mixing ratios were generally  $<50$  pptv [Dibb *et al.*, 1999a]. The time resolution of these measurements was typically 10–15 min, so their inclusion in the  $\text{NO}_y$  discussion in this paper is difficult. In only a few cases in the combustion plume data set was particle  $\text{NO}_3^-$  greater than 10% of the  $\text{NO}_y$  sum. It appears that wet scavenging of particle  $\text{NO}_3^-$  occurred early in the life of the biomass burning emissions, with only an occasional plume containing  $>50$  pptv of particle  $\text{NO}_3^-$  [Dibb *et al.*, 1999b].

### 3.2. Vertical Distributions

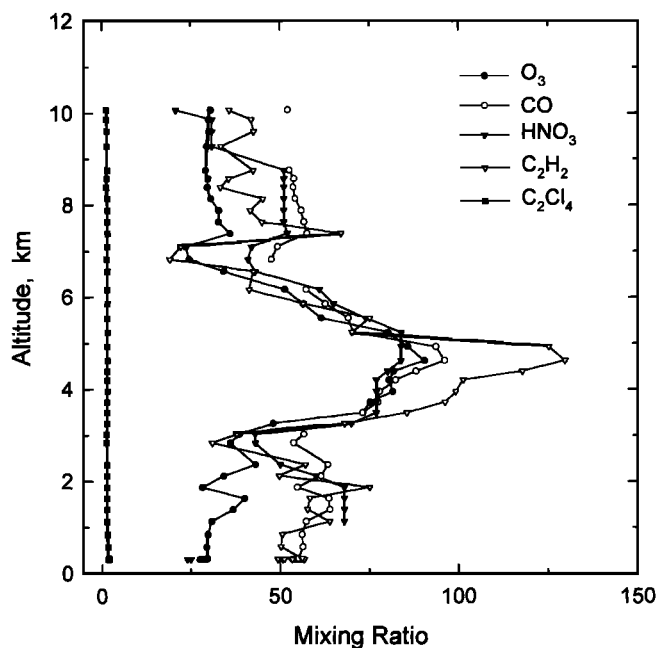
Figure 1 illustrates the vertical distribution encountered commonly over the South Pacific for species associated with combus-

tion emissions. This plume was encountered west of Tahiti on a spiral ascent during mission 6 and was particularly well defined by  $\text{C}_2\text{H}_2$ , a unique tracer of combustion emissions [Blake *et al.*, 1996a]. Note that  $\text{C}_2\text{Cl}_4$ , an industrial emissions tracer, was not elevated between 3 and 6 km altitude with the other trace gases. The biomass burning tracer  $\text{CH}_3\text{Cl}$  [Blake *et al.*, 1996b] fluctuated between 550 and 575 pptv over the entire spiral altitude but did not show a pronounced plume like the other combustion-associated species. In other cases,  $\text{CH}_3\text{Cl}$  exhibited a higher correlation with these species in plumes. The large-scale distribution of nonmethane hydrocarbons and selected halocarbons over the South Pacific during PEM-Tropics A is presented elsewhere [Blake *et al.*, 1999], where multiple spiral data illustrate the apparent impact of biomass burning emissions in the middle and upper troposphere.

It is important to recognize that the plumes sampled during PEM-Tropics A were aged from 1 to 2.5 weeks since they last passed over land based on model calculations of air parcel trajectories [Fuelberg *et al.*, 1999] and independent estimates using a combination of radioactive ingrowth of  $^{210}\text{Pb}$  and OH decomposition of selected hydrocarbons [Dibb *et al.*, 1999b]. The air parcels sampled over the South Pacific last passed over land in Africa, Australia, or Indonesia, all regions of active biomass burning during austral springtime [Fuelberg *et al.*, 1999]. In addition, lightning associated with convection in these areas was very abundant [Fuelberg *et al.*, 1999], and it could have contributed reactive nitrogen to the plumes that we encountered over the South Pacific.



**Plate 2.** Relationship between selected species and  $C_2H_2$  over the South Pacific. Blue dots are nonplume data, and red dots are from within combustion plumes.



**Figure 1.** Vertical distribution of selected trace gases during a spiral ascent on mission 6 just west of Tahiti at 15°S and 155°W. Mixing ratios of  $O_3$  and CO are in parts per billion by volume, and the other species are in parts per trillion by volume.

It was rare to find elevated  $NO_x$  mixing ratios in these plumes due to the potentially long time periods from its injection from combustion or lightning over continental areas. During transport of this duration it should have been converted to  $HNO_3$ , PAN, and possibly other reactive nitrogen forms. Indeed, the absence of significant aerosols in these plumes but elevated mixing ratios of  $HNO_3$  (e.g., Figure 1) indicate photochemical production of  $HNO_3$  during long-range transport after being scavenged initially by convection over continental areas [Talbot *et al.*, 1999b].

The vertical distributions of  $NO_x$ ,  $HNO_3$ , PAN,  $CH_3ONO_2$ , and  $C_2H_5ONO_2$  over the South Pacific are presented in Figures 2a (nonplume) and 2b (within plumes). In general, the mixing ratio of  $NO_x$  in nonplume air parcels was <50 pptv, with much of the data <20 pptv. Mixing ratios were <5 pptv in the marine boundary layer, increasing to an average of 25 pptv in the upper troposphere. It was not uncommon to have areas in the marine boundary layer where the mixing ratio of  $NO$  was <1 pptv and as low as 0.2 pptv [Bradshaw *et al.*, 1999].

The mixing ratios of  $HNO_3$  and PAN were usually <100 pptv, but larger departures from this value are evident in the nonplume air parcels. Notice that in the middle troposphere (3–10 km),  $HNO_3$  and PAN are both present at several hundred parts per trillion by volume. In the marine boundary layer, PAN was <5 pptv and  $HNO_3$  was <20 pptv. Thermal decomposition of PAN occurs on the order of hours in this warm (25°–30°C), moist region, which should lead to  $HNO_3$  production from the  $NO_2 + OH$  mechanism. The mixing ratio of  $HNO_3$  is, however, kept <20 pptv due to its deposition to the ocean and uptake onto salt aerosol in the boundary layer [Talbot *et al.*, 1999b]. Below 4 km altitude the  $NO_x$  responsible for  $O_3$  production is largely explained by the decomposition of PAN [Schultz *et al.*, 1999].

The mixing ratios of  $NO_x$ ,  $HNO_3$ , and PAN in the nonplume air parcels over the South Pacific in the middle and upper troposphere were comparable to those typically found at remote locations.  $NO_x$ ,

$HNO_3$ , and PAN are typically 50–100 pptv at Mauna Loa [Atlas *et al.*, 1992a] and over the North Pacific in aged marine air [Talbot *et al.*, 1996a, 1997b]. The principal difference in the reactive nitrogen distributions over these Pacific regions is for  $NO_x$  in the marine boundary layer. With the South Pacific being by far the most remote of these locations,  $NO_x$  mixing ratios are twofold to fivefold lower.

The alkyl nitrate distribution over the South Pacific was dominated by  $CH_3ONO_2$ , which averaged from 15 pptv in the marine boundary layer to around 10 pptv from 2 to 12 km altitude. The only other significant alkyl nitrate was  $C_2H_5ONO_2$ , with its distribution mainly <5 pptv at all altitudes.

Looking at the vertical distributions of reactive nitrogen species in the combustion plume air parcels (Figure 2b) shows that  $NO_x$  was very similar to the nonplume group. The difference in the two groups' altitude bin means is <10 pptv above 2 km, with the plume data exhibiting the slightly higher values. The differences are even less for the two alkyl nitrates but in the opposite direction, with about 3 pptv less, on average, in the plume data vertical distribution of  $CH_3ONO_2$ .

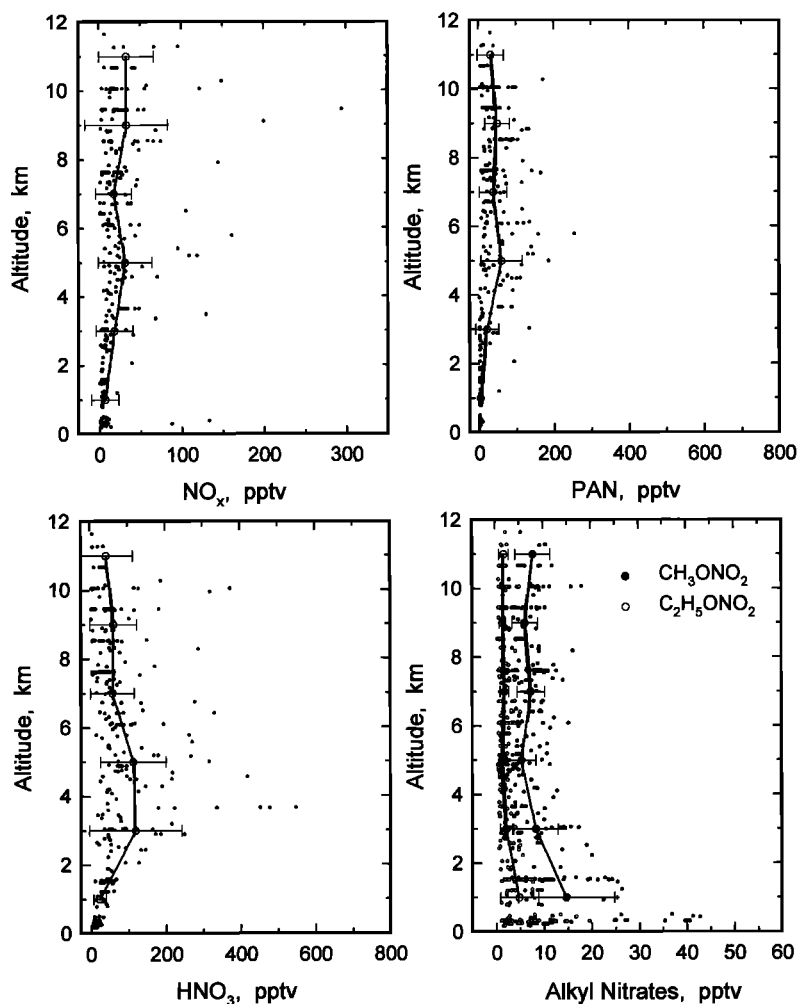
The largest differences in the vertical distributions between the two groups is in the middle troposphere where  $HNO_3$  and PAN were enhanced in the plume data set. The greatest mixing ratios of  $HNO_3$  and PAN were observed in the 2–8 km altitude region. We found average mixing ratios of  $HNO_3$  of 175 pptv and 165 pptv for PAN compared with 100 and 50 pptv, respectively, in the nonplume air parcels. Mixing ratios of  $HNO_3$  and PAN around 500 pptv over the South Pacific are among the largest ever observed in the remote middle troposphere (Figure 2b). This is quite remarkable considering that the South Pacific is one of the most isolated locations on Earth. Here the large-scale flow pattern dominated by westerlies [Fuelberg *et al.*, 1999] apparently brings quite aged continentally derived combustion emissions to the South Pacific during the austral springtime period. This source influence is barely perceptible in  $NO_x$  and alkyl nitrates but is easily noticeable in  $HNO_3$  and PAN.

The vertical distributions of the  $NO_y$  sum in the nonplume and plume air parcel classifications are shown in Plate 1. In the marine boundary, which is somewhat isolated from the polluted conditions above it by the trade wind inversion, the  $NO_y$  sum averaged ~50 pptv in both air parcel types. The impact of the combustion plumes was significant from 2 to 12 km altitude. In this region, the  $NO_y$  sum averaged 285 pptv in the plumes compared with 120 pptv in nonplume air parcels. Values of the  $NO_y$  sum of 100–150 pptv are typical of air parcels over remote regions not recently influenced by emission sources [Atlas *et al.*, 1992a; Ridley, 1991; Talbot *et al.*, 1996a, 1997b, 1999a].

### 3.3. $NO_y$ Partitioning

To examine the relationship of various species to  $NO_y$ , the vertical distributions of their ratio to the  $NO_y$  sum are shown in Figures 3a (nonplume) and 3b (within plumes). In the nonplume data the ratio  $NO_x/NO_y$  sum is 10–15% from the boundary layer to 7 km altitude, and then it increases to 25% at 12 km. Owing to slightly larger  $NO_x$  mixing ratios in the plume data, especially above 5 km, the ratio  $NO_x/NO_y$  sum is ~8–10% from the boundary layer to 7 km, and then it again increases to 25% at 12 km. The opposite trend is seen for the alkyl nitrates, decreasing from ~30–40% in the boundary layer to ~5% above 3 km altitude. In the nonplume data the ratio was higher at all altitudes by about 3–5%, presumably driven by a stronger marine source for these species compared with combustion plumes over the South Pacific.

The ratio  $HNO_3/NO_y$  sum in the nonplume air parcels has a value



**Figure 2a.** Vertical distribution of reactive odd nitrogen species in nonplume air parcels over the South Pacific. The open circles represent the average value  $\pm$  one standard deviation for 2 km altitude bins.

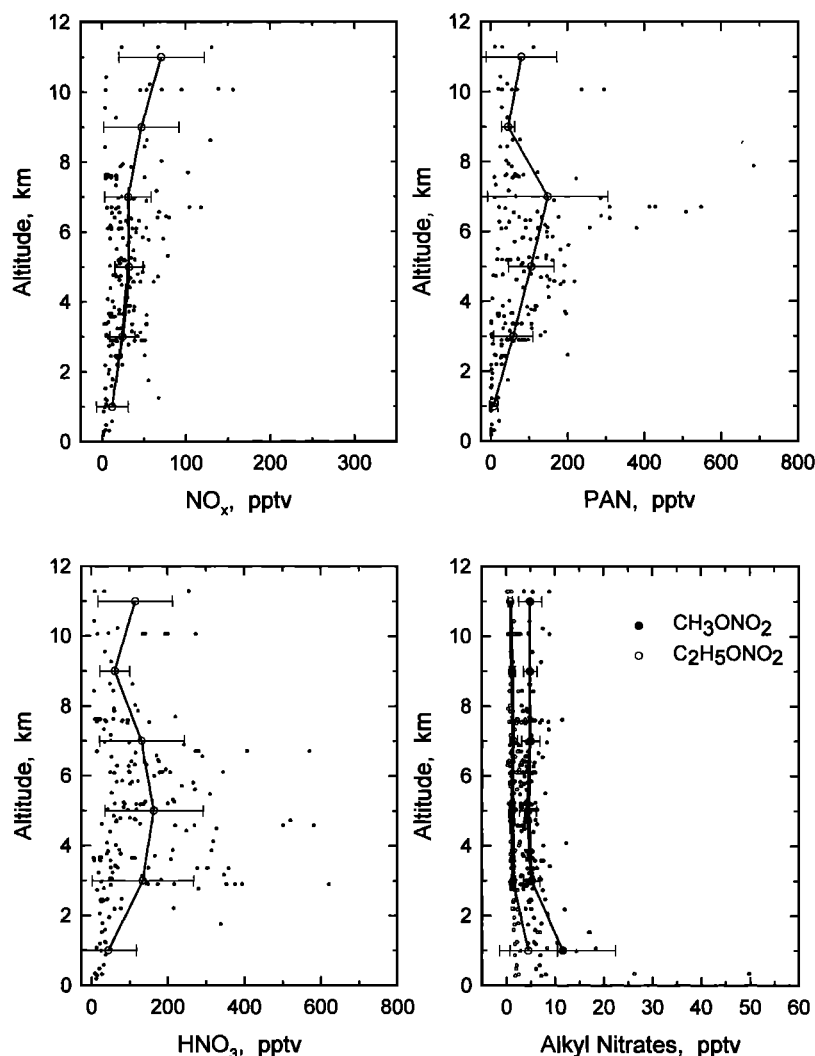
of  $\sim 50\%$  in the boundary layer that increases to  $70\%$  in the 2–4 km region and then decreases linearly to  $\sim 25\%$  at 12 km altitude. The sharp increase in the value of this ratio near 3 km may reflect the influence of cloud processes in this layer. Small cumulus with bases at the top of the marine boundary layer (1–1.5 km) may be releasing soluble gases to the gas phase as cloud tops in this transition layer dissipate at 3–4 km. Chemical and dynamical processes in this cloudy region are known to produce aerosols [Clarke *et al.*, 1999], and it seems likely that soluble gases would also be released by these same mechanisms. In the plume air parcels this effect is less noticeable due to elevated mixing ratios in and above this region. The ratio  $\text{HNO}_3/\text{NO}_x$  sum is still  $\sim 50\%$  in the boundary layer, but this value is maintained up to 6 km before decreasing to  $\sim 40\%$  at 12 km altitude. Thus there is a major impact on the  $\text{NO}_x$  partitioning above the marine boundary layer attributed to combustion/lightning inputs of reactive nitrogen.

The impact of the same inputs on the  $\text{PAN}/\text{NO}_x$  sum is less, even in the middle troposphere. This ratio is 5–10% in the boundary layer, increasing to 30–40% in the middle troposphere before decreasing to  $\sim 20\%$  at 12 km altitude. In the middle troposphere, long-range transport appears to increase the ratio  $\text{PAN}/\text{NO}_x$  sum by about 10% in the plume air parcels compared with the nonplume cases.

#### 4. Species Interrelationships

Comparisons between the nonplume and plume data sets shows that a very similar combustion influence is present in both air parcel classifications. Various species interrelationships demonstrate this point in Plate 2. In each of the correlations shown in Plate 2 the nonplume and plume distributions overlap fairly tightly, with the highest mixing ratios of  $\text{C}_2\text{H}_2$ , and the other parameters associated with the plume air parcels. The correlation of  $\text{CH}_3\text{Cl}$  and  $\text{C}_2\text{H}_2$  indicates that a biomass burning source is responsible for at least some portion of the chemical signatures. The lack of similar correlation of  $\text{C}_2\text{H}_2$  with industrial tracers (e.g., Figure 1) suggests that the combustion influence is mainly derived from biomass burning.

As can be seen in Plate 2, there was a substantial amount of  $\text{O}_3$  associated with these plumes, a chemical characteristic of biomass burning emissions from South America and Africa [Fishman and Brackett, 1997]. In fact, about half of the  $\text{O}_3$  in the tropospheric column over the South Pacific appears to have been advected eastward in biomass burning emissions from South America and Africa [Schultz *et al.*, 1999]. The apparent dispersion of these emissions throughout most of the tropospheric column over the South Pacific is likely due to mixing and dilution of combustion



**Figure 2b.** Vertical distribution of reactive odd nitrogen species in combustion plumes over the South Pacific. The open circles represent the average value  $\pm$  one standard deviation for 2 km altitude bins.

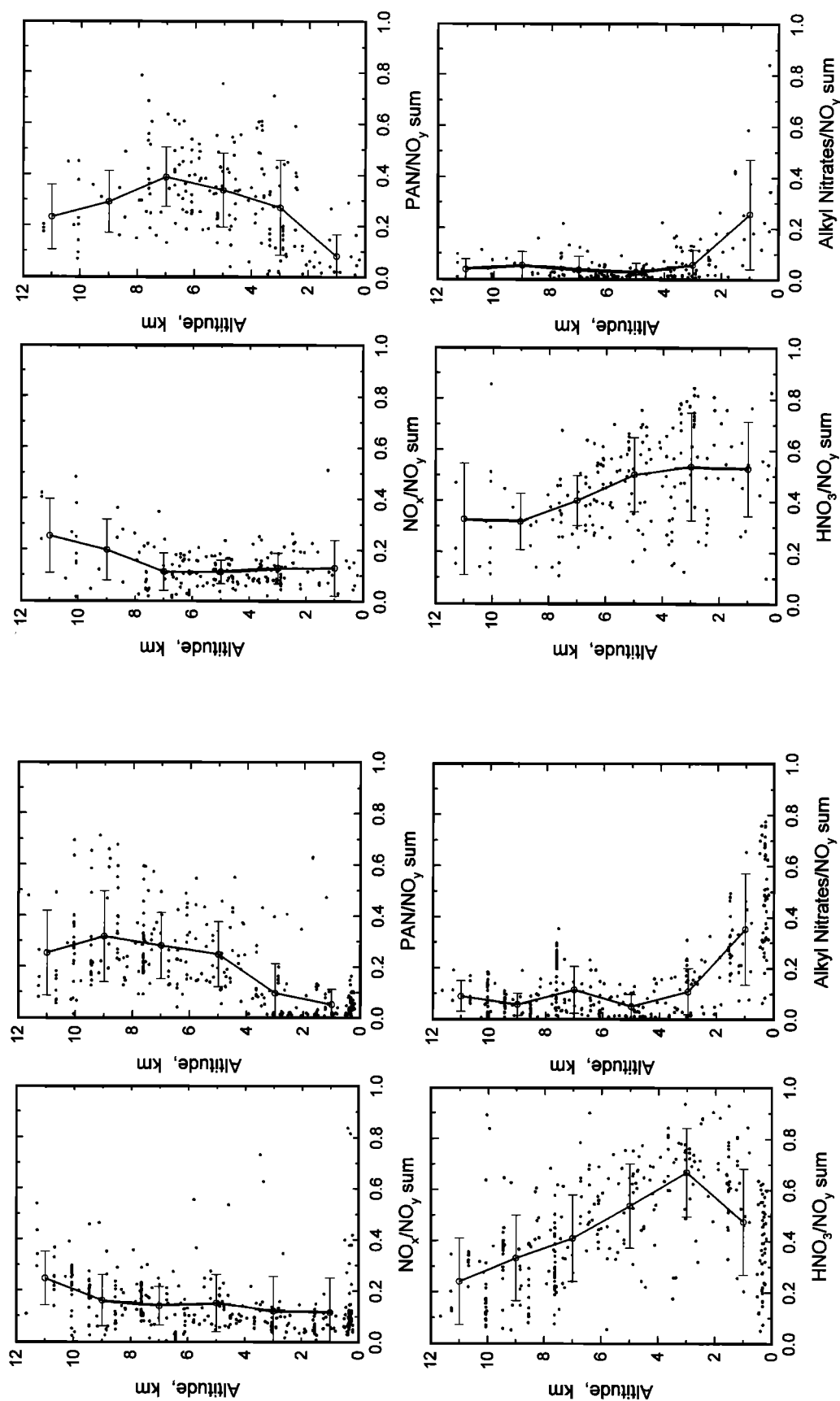
plumes with surrounding ambient air. The nonplume data chemical signature reflects this combustion influence. This is particularly pronounced for the  $\text{NO}_x$  sum, where data from both data classifications overlap significantly. The wide scatter in the  $\text{C}_2\text{H}_2/\text{NO}_x$  sum relationship is probably driven to a large degree by varying loss or production of  $\text{HNO}_3$  and PAN. Plots of these two species against  $\text{C}_2\text{H}_2$  (not shown) show scatter similar to that for the  $\text{NO}_x$  sum.

The relationships of  $\text{CH}_3\text{Cl}$  with PAN and the  $\text{NO}_x$  sum are presented in Plate 3. The extensive scatter in the relationship for the  $\text{NO}_x$  sum is similar to that with  $\text{C}_2\text{H}_2$  (Plate 2). Slightly better correlation is found for PAN ( $r^2 = 0.35$ ), but it is driven mainly by the highest values in both species. The GTE program investigated the chemical environment over the South Atlantic during the 1992 austral spring. Biomass burning pollution was evident throughout the tropospheric column, with  $\text{CH}_3\text{Cl}$  mixing ratios in the 600–700 pptv range [Talbot *et al.*, 1996b]. If we take a value of 650 pptv over the biomass burning source areas and 560 pptv over the South Pacific, this represents a 14% decrease in  $\text{CH}_3\text{Cl}$  over about a 2-week period. Attack by OH (at, say,  $1 \times 10^6 \text{ cm}^{-3}$ ) can account for maybe half of this drop, with the rest attributed to dilution. These

rough estimates are consistent with other air mass history analyses, where OH attack and dilution were found to be equally responsible for decreases in hydrocarbon species [e.g., McKeen and Liu, 1993]. Thus the mixing ratios of  $\text{CH}_3\text{Cl}$  over the South Pacific are in the range expected for a South American/African biomass burning source.

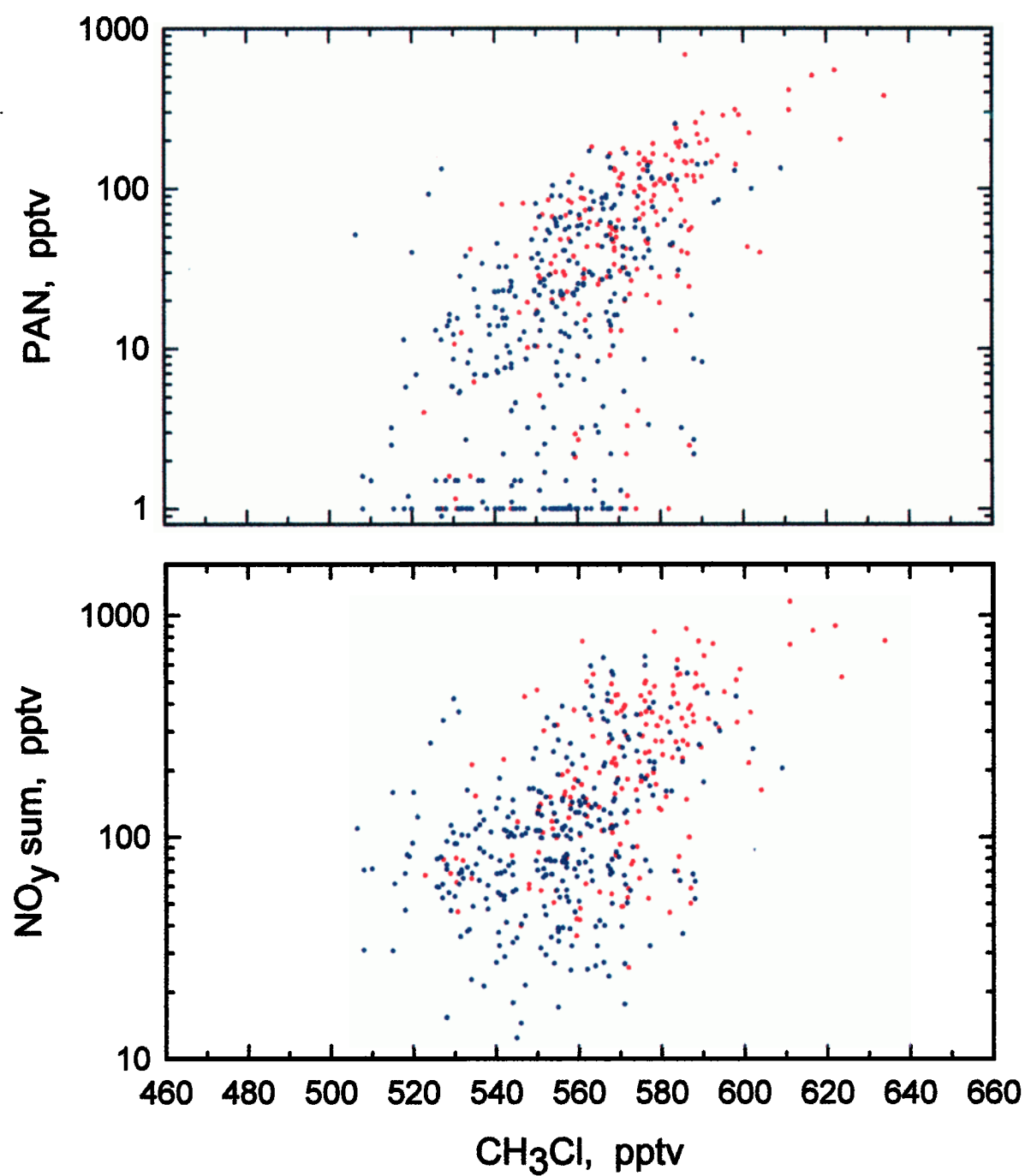
These same air parcels could have had inputs of reactive nitrogen besides that from biomass burning. In some cases, lightning may have provided an additional source of reactive nitrogen. Additionally, we cannot rule out the stratosphere as a source of reactive nitrogen. Levels of  $^7\text{Be}$ , a reasonably good stratospheric tracer in the troposphere, frequently exceeded 400 fCi ( $10^{-15} \text{ Ci}$ )  $\text{m}^{-3}$  throughout much of the tropospheric column (Plate 4). Such concentrations of  $^7\text{Be}$  are quite elevated, being 2–3 times higher than we have observed previously over the North Pacific [Talbot *et al.*, 1996a, 1997b]. Even though the correlation of the  $\text{NO}_x$  sum with  $^7\text{Be}$  is not very robust (Plate 4), the high  $^7\text{Be}$  concentrations still leave open the possibility that the stratosphere could have been a source of reactive nitrogen. A somewhat better correlation (a second-order fit gives  $r^2 = 0.41$ ) is found between the  $\text{NO}_x$  sum and  $^{210}\text{Pb}$ , a tracer of



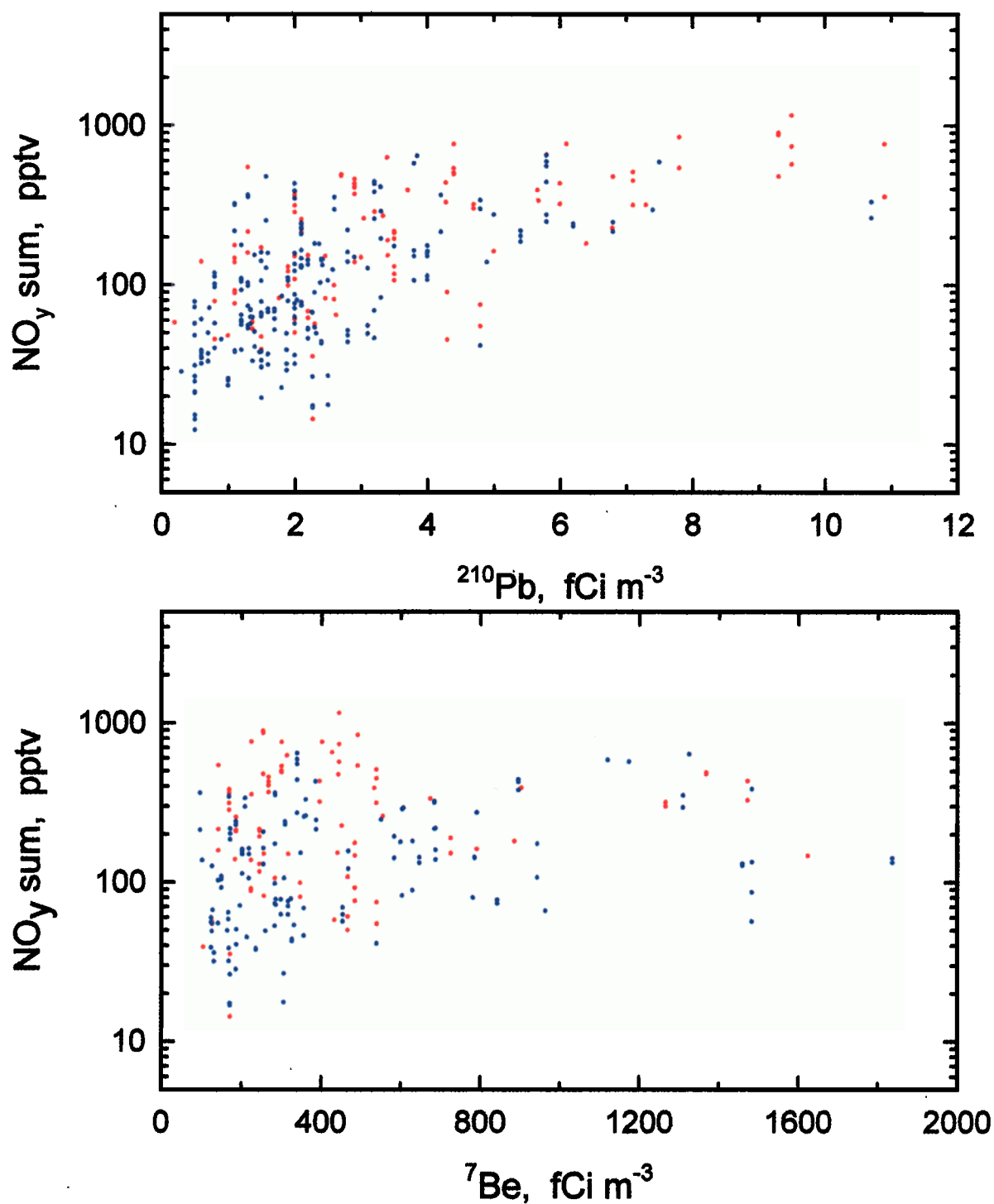


**Figure 3b.** Ratio of reactive odd nitrogen species to the  $\text{NO}_y$  sum in combustion plumes over the South Pacific. The open circles represent the average value  $\pm$  one standard deviation for 2 km altitude bins.

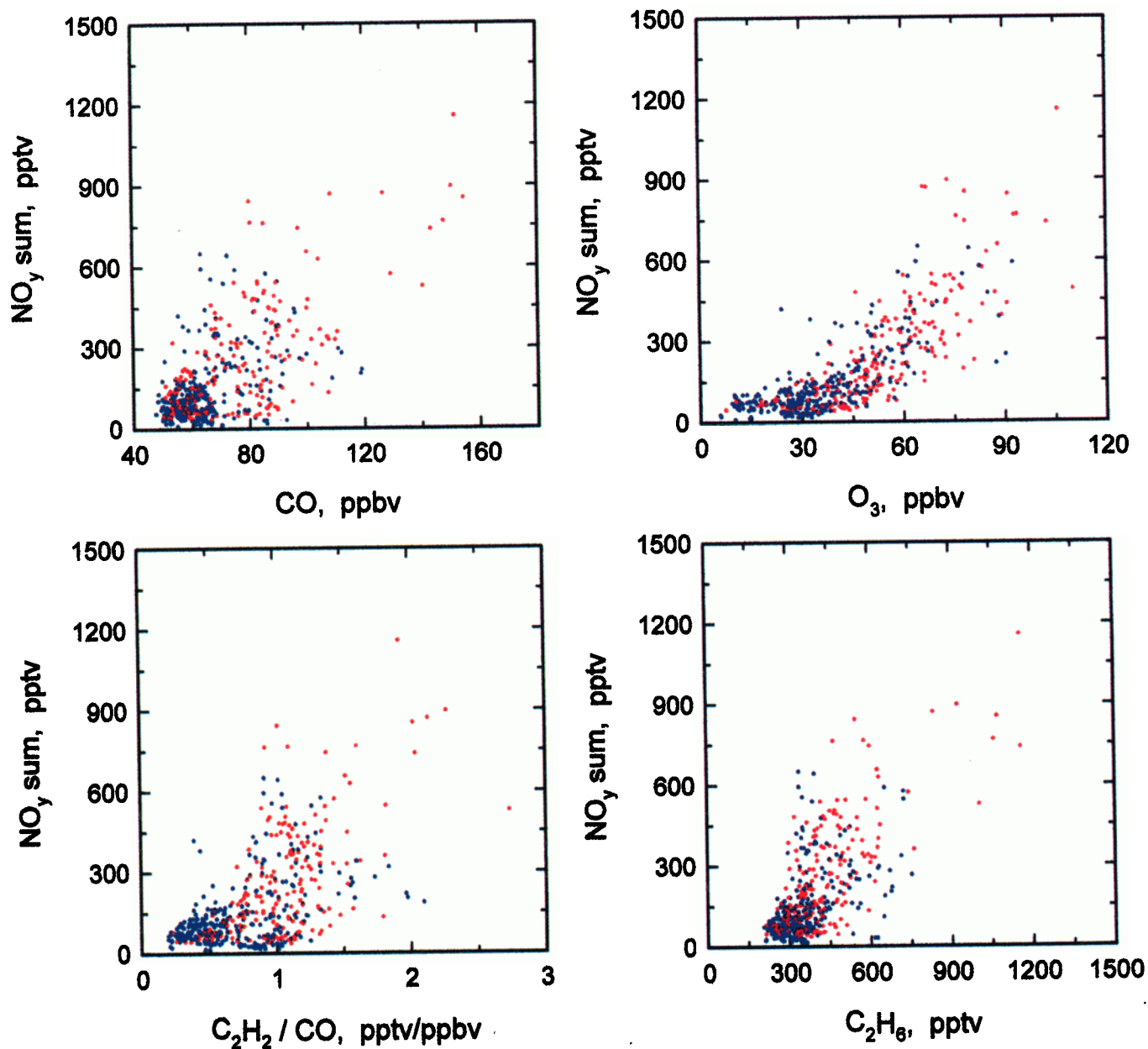
**Figure 3a.** Ratio of reactive odd nitrogen species to the  $\text{NO}_y$  sum in nonplume air parcels over the South Pacific. The open circles represent the average value  $\pm$  one standard deviation for 2 km altitude bins.



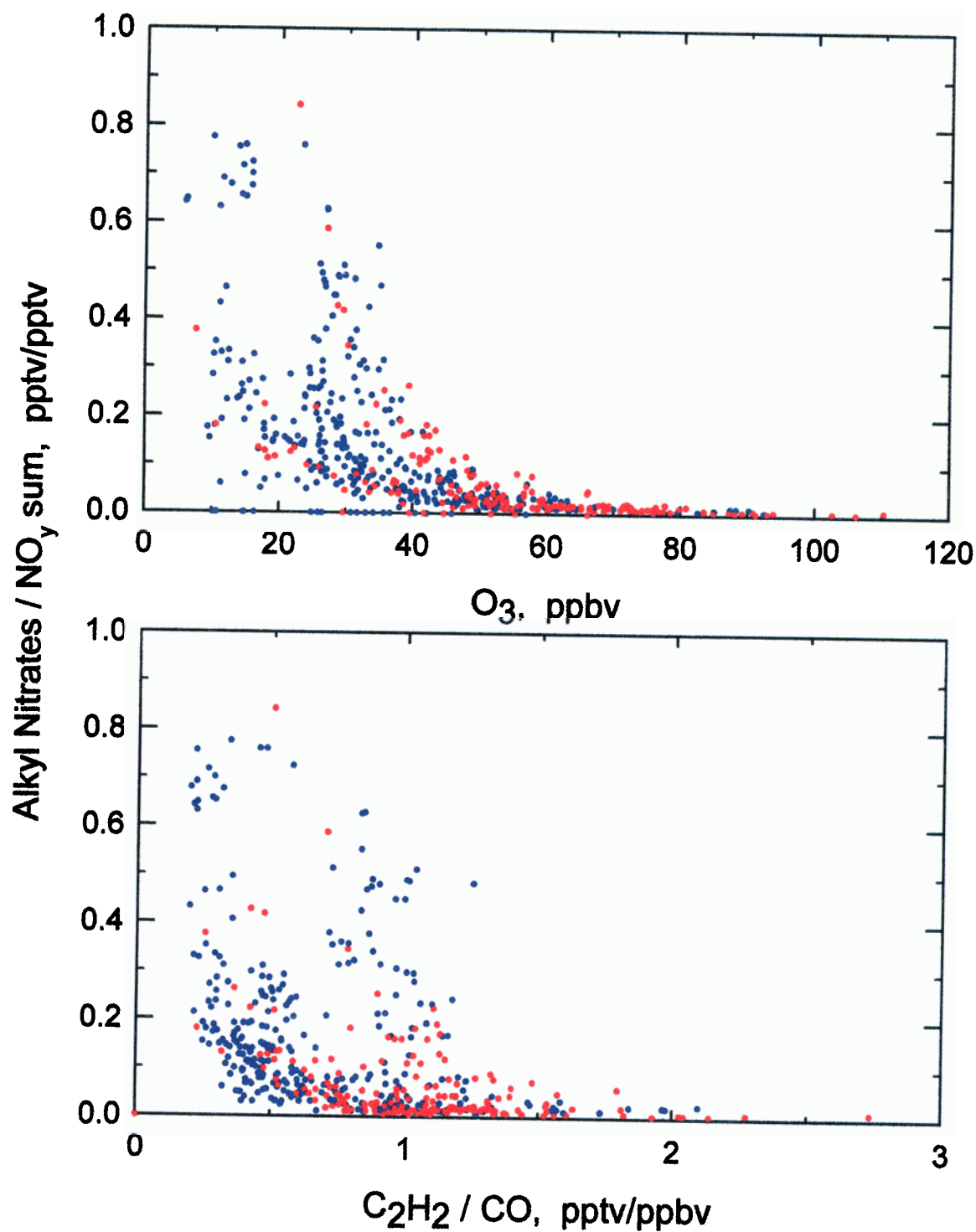
**Plate 3.** Relationship between PAN and the  $\text{NO}_y$  sum with  $\text{CH}_3\text{Cl}$  over the South Pacific. Blue dots are nonplume data, and red dots are from within combustion plumes. Note that the plot has a semilogarithmic scale.



**Plate 4.** Relationship between the NO<sub>y</sub> sum and <sup>210</sup>Pb, a continental tracer, and <sup>7</sup>Be, a tracer of stratospheric inputs to the troposphere. Blue dots are nonplume data, and red dots are from within combustion plumes. Note that the plot has a semilogarithmic scale.



**Plate 5.** Relationship of the  $\text{NO}_y \text{ sum}$  to selected pollution-associated species over the South Pacific. Blue dots are nonplume data, and red dots are from within combustion plumes.



**Plate 6.** Ratio of alkyl nitrates ( $\text{CH}_3\text{ONO}_2 + \text{C}_2\text{H}_5\text{ONO}_2$ ) to the  $\text{NO}_y$  sum as a function of  $\text{O}_3$  and  $\text{C}_2\text{H}_2/\text{CO}$ . Blue dots are nonplume data, and red dots are from within combustion plumes.

continental emissions [Dibb *et al.*, 1996]. Both data classifications support this relationship, endorsing the idea that the chemistry of the nonplume air parcels was strongly influenced by plume dissipation. This correlation indicates that continental combustion emissions were probably an important source of the  $\text{NO}_x$  sum, but the distinction between combustion and lightning inputs cannot be uniquely resolved. With possible multiple sources of the  $\text{NO}_x$  sum without concomitant  $\text{CH}_3\text{Cl}$  inputs, it is not surprising that the correlation in these two species is weak over the South Pacific (Plate 3).

Relationships of the  $\text{NO}_x$  sum with other selected parameters are depicted in Plate 5. As with  $\text{CH}_3\text{Cl}$ , the relationships exhibit significant scatter except for that with  $\text{O}_3$ . Again, we attribute this scatter to multiple possible sources for the  $\text{NO}_x$  sum and the aged nature of the air parcels from dilution and OH decomposition of CO and hydrocarbons. Despite the fact that well-defined relationships are not present, it is clear that the most aged air parcels with  $\text{C}_2\text{H}_2/\text{CO}$  ratios  $<0.5$  contain the lowest mixing ratios of the  $\text{NO}_x$  sum. The majority of the nonplume data fall into this category, where most of the reactive nitrogen has probably been converted to  $\text{HNO}_3$  and subsequently lost from the atmosphere by wet and dry deposition processes.

Quite a different picture appears to be plausible for the alkyl nitrate species. In this case they appear to comprise the largest fraction of the  $\text{NO}_x$  sum coincident with the smallest mixing ratios of  $\text{O}_3$  and values of the ratio  $\text{C}_2\text{H}_2/\text{CO}$  (Plate 6). This, of course, corresponds to air parcels in the marine boundary layer which contain direct marine emissions of alkyl nitrates and are somewhat isolated from the air above (by temperature inversions), are photochemically aged (low  $\text{C}_2\text{H}_2/\text{CO}$ ), and contain low  $\text{O}_3$  due to chemical and surface deposition losses. It should be noted that aerosol  $\text{NO}_3^-$  mixing ratios were very similar to those for the alkyl nitrates in the marine boundary layer, generally ranging from 20 to 50 pptv [Dibb *et al.*, 1999a]. Thus these nitrate compounds together comprise nearly all of the  $\text{NO}_x$  sum in this lower tropospheric region.

In the most aged air masses sampled with  $\text{C}_2\text{H}_2/\text{CO} < 0.5$ , alkyl nitrates often composed  $>20\%$  of the  $\text{NO}_x$  sum. The majority of the alkyl nitrate plume data contained low mixing ratios and ratio values to the  $\text{NO}_x$  sum. The majority of the data with the greatest alkyl nitrate/ $\text{NO}_x$  sum ratios were in the nonplume air parcel classification. There appear to be two different distributions, one with  $\text{C}_2\text{H}_2/\text{CO}$  ratio values  $<0.5$  and the other with a ratio value of  $\sim 1.0$  (Plate 6). Most of the data associated with ratio values around 1.0 were collected at high latitude ( $50^\circ$ – $70^\circ\text{S}$ ) during a flight south of New Zealand to Antarctica where the  $\text{NO}_x$  sum was  $<70$  pptv. The other distributions at lower  $\text{C}_2\text{H}_2/\text{CO}$  ratio values are from flights in the tropical South Pacific region. Thus it appears that alkyl nitrates are important reactive nitrogen species in the marine boundary layer in equatorial and high-latitude regions of the Pacific Ocean. Although this point has been speculated on previously [Atlas, 1988], the PEM-Tropics A data are a first definitive demonstration of it.

## 5. Conclusion

This paper presents the distribution of reactive odd nitrogen species over the South Pacific Ocean during austral springtime. Mixing ratios of  $\text{NO}_x$  were generally low ( $<20$  pptv) throughout the tropospheric column (0–12.5 km), with little evidence for a dominant source. The absence of clear chemical signatures correlated with the  $\text{NO}_x$  distribution is attributed to the 1- to 2.5-week-

old age of the sampled air parcels. The distributions of  $\text{HNO}_3$  and PAN indicate an important biomass burning source for reactive nitrogen in the free troposphere, although contributions from lightning and the stratosphere cannot be ruled out. In the marine boundary layer, alkyl nitrate species are a major component of the  $\text{NO}_x$  sum, with this natural oceanic source especially important in equatorial and high-latitude regions.

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